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Comparative study of retrofitting strategies for seismic risk management of road networks

R. Silva-Lopez[1] and J. Baker[2]

ABSTRACT

This article presents a comparative study of three retrofitting strategies for seismic risk management of road networks that have been studied by the authors, (1) Corridors-supported optimization, (2) LIME-TI retrofitting ranking, and (3) Optimization using genetic algorithms. To perform the comparison, three aspects of the retrofitting techniques are analyzed, (i) the ability of the strategy to minimize expected annual traffic disruption, (ii) computational costs involved in the implementation of the strategies, and (iii) interpretability of bridges selected to retrofit from the perspective of policymaking. From the comparison, using genetic algorithms yields smaller traffic disruption than the other two approaches; however, computational costs involved in the implementation of this technique are significantly higher than the others. Regarding interpretability of selected bridges to retrofit, using Corridors resembles current retrofitting policies that intervene segments of road networks. Although this study focuses on comparing three specific optimization techniques, the approach taken to evaluate their performance can be used to evaluate other strategies.

Introduction

Road networks are critical for cities, allowing the flow of goods and people throughout a region [1]. Unfortunately, these systems are vulnerable to earthquake damage and disruption [2], profoundly affecting communities and their ability to recover from these shocks [3,4]. Motivated by this risk, decision-makers have explored different ways in which network disruption can be minimized using public resources efficiently. One proposed approach to achieve this objective has been to use optimization to detect bridges to retrofit so the expected network disruption can be minimized [5,6,7]. While different optimization techniques have been proposed, their benefits and shortcomings have not been compared. The main contribution of this study is to propose and implement a comparison methodology for optimal retrofitting strategies. To illustrate this comparison method, three optimization strategies are selected as an example, evaluating them in terms of the improvement in network performance they induce, the computational cost involved in their implementation, and the interpretability of the results that each strategy suggests.

Methods

Overview

To compare different retrofitting strategies, it is necessary to propose and implement seismic risk assessment procedures to quantify the effects of retrofitting bridges. In this case study, three retrofitting strategies are considered

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[1] Ph.D. Candidate, Dept. of Civil and Environmental Engineering, Stanford University, Stanford, CA, 94305 (rsilval@stanford.edu)
[2] Professor, Dept. of Civil and Environmental Engineering, Stanford University, Stanford, CA, 94305

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to select bridges to undergo retrofitting: (i) Corridors-supported optimization [8], (ii) LIME-TI Ranking retrofitting [9], and (iii) Optimization using genetic algorithms [10]. These optimization techniques have been developed by the authors and are explained in detail as individual studies. After bridges have been selected, an evaluation of the seismic performance improvement of the road network is performed using the proposed seismic risk assessment procedure. Finally, retrofitting strategies are compared between each other in terms of (i) improvement of road network performance computed in, (ii) computational costs involved in their implementation, and (iii) interpretability of the proposed bridges to retrofit for the purposes of facilitating decision-making and policymaking. The comparison of retrofitting strategies is performed for a model of the San Francisco Bay Area Road Network [11].

Seismic risk assessment of road networks

Quantifying the effect of retrofitting bridges requires a seismic risk assessment framework to determine improvements induced by strengthening bridges. In this study, the assessment framework follows the proposal by Miller [11], where for a series of hazard-consistent scenarios, a spatially correlated ground motion map is obtained. Then using intensity metrics at the locations of each bridge and their fragility functions, realizations of damage are sampled. Over these damaged versions of the network, trips of users between different origins and destinations are simulated using a traffic model. Based on trips performed by users, aggregated regional information can be obtained such increase in travel time and trips lost. Retrofitting bridges enhances their fragility functions and reduces their likelihood of experiencing damage This provides a quantifiable metric to evaluate improvements induced by each retrofit strategy. Using a set of hazard-consistent scenarios, a value of expected annual traffic performance change can be obtained. In terms of this study, a bigger change of this metric implies a bigger disruption. Figure 1 illustrates the seismic risk assessment framework.

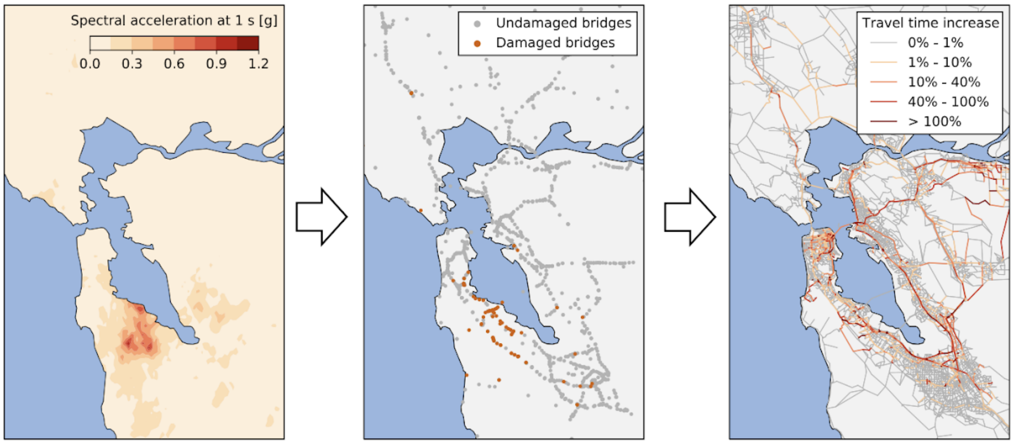

Figure 1. Seismic risk assessment of a road network. [9]

Corridors-supported Optimization

The first optimization technique included in this comparison is the Corridors-supported optimization [8]. This technique uses a two-staged stochastic optimization to detect groups of bridges, or Corridors, that need to be retrofitted to ensure an acceptable level of network performance while minimizing the cost of retrofitting actions. A Corridor is defined as a group of bridges that work jointly to provide a transportation service such as ensuring adequate connectivity or traffic flow between different areas of a region. Corridors are detected using a Markov Clustering algorithm [12], a method that uses random walks to detect interconnected nodes within a graph. Figure 2 further illustrates the definition of a Corridor.

The proposed optimization strategy has as an objective function the minimization of cost of retrofitting bridges or expected cost of repairing them in case of damage and uses two constraints to implement the Corridors strategy. The first constraint limits the acceptable increase in travel time for fixed sets of origins and destination of interest, and the second constraint enforces that all bridges within a Corridor need to be retrofitted jointly. Further information about this optimization retrofitting strategy can be found in [8].

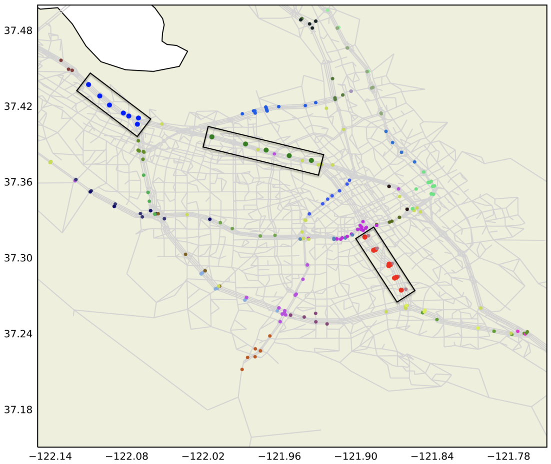

Figure 2. Corridors in the city of San Jose, where each color represents a bridge Corridor, and some corridors are selected with boxes to further clarify what a Corridor is

LIME-TI Ranking

The second optimal retrofitting strategy included in this comparison is the LIME-TI Ranking [9]. The LIME-TI ranking arises from the implementation of a modified variable importance algorithm LIME [13] on a deep neural network calibrated to predict traffic disruption associated with a damaged state of the network. Bridges selected by LIME-TI are among the bridges that have the biggest contribution to the expected annual change of traffic performance metric, which explains their importance to the predictions of the neural network. This strategy was developed in a previous study [9]. Although the implementation of LIME-TI itself is not computationally expensive, it relies on the use of a calibrated deep neural network trained using extensive computational resources.

Optimization using genetic algorithms

The final retrofitting strategy included in this study is the one that uses a genetic algorithm to directly minimize the expected annual change of the traffic performance network for the road network [10]. To use the genetic algorithm as a retrofitting strategy, each chromosome is a set of bridges to retrofit, with each gene being an integer that identifies the bridge that is being retrofitted. To improve efficiency, a surrogate model allows rapid and accurate estimates of traffic performance, such as the deep neural network developed in [9]. Note that while previous retrofitting strategies used approximate optimization to find bridges to retrofit, the optimization that uses genetic algorithms directly minimizes the annual expected change in traffic performance. However, despite yielding a better network performance, this strategy is highly computationally expensive since it relies on having a calibrated surrogate model, and the convergence time of the genetic algorithm grows exponentially as a function of the number of bridges retrofitted. More details about the interpretation of genetic algorithms can be found in [10]

Results

Comparison of strategies

Change of expected traffic performance

The results of the change of traffic performance metric are presented in Figure 3, which shows that the change in traffic performance using genetic algorithms is minimized compared to using the Corridors-optimization or the LIME-TI ranking, with lower values showing a lower disruption. This is reasonable if we consider the implementation using genetic algorithms directly minimizes the metric shown in Figure 3. Another observation of Figure 3 is that the Corridors-optimization is a more effective strategy than LIME-TI ranking, which is a result of ranking techniques not being able to capture the interdependency between bridges, which the Corridor approach does.

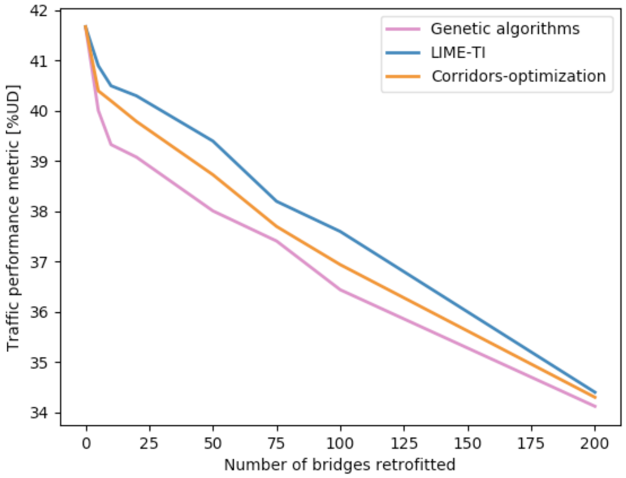

Figure 3. Comparison of change of expected annual change in traffic performance metric

Computational costs involved in the implementation

Regarding the computational costs for each optimization strategy, both LIME-TI ranking and the optimization that uses genetic algorithms need a calibrated deep neural network which is computationally expensive to train, requiring 40 hours of training in a MacBook Pro (2016), with a 2.6 GHz Quad-Core Intel Core i7 processor. In addition, genetic algorithms require many generations to converge [14], and this would take 336 hours with the above-mentioned processor (though in this application a High-Performance Computing facility was used for training). The technique that requires the least computational resources for a single number of retrofitted bridges is Corridors-optimization, which takes 16 hours to generate its inputs and 6 hours to select bridges. If several sets of bridges need to be selected, then the LIME-TI technique can become more efficient after the costs of running several Corridors-optimization surpass the implementation of LIME-TI, since once the neural network has been calibrated, the computational cost required to select bridges with the LIME-TI is minimal.

Interpretability of selected bridges to retrofit

The interpretability of results varies for each retrofitting strategy. Corridors-optimization draws inspiration from current practices in bridge retrofitting. Therefore the results of this technique have direct practical considerations. Contrarily, bridge retrofit selection using genetic algorithms or LIME-TI cannot be explained in intuitive terms, as shown in [9,10]. These explanations are secondary to the results of the optimization and are subject to the specific number of bridges selected to retrofit. Therefore, in terms of interpretability, using a Corridors-optimization resembles what can be applied by management agencies [15,16] more directly than the other strategies.

Conclusions

This study introduces a methodology to compare bridge retrofitting strategies in terms of traffic performance, computational costs, and interpretability of results. To illustrate, three optimization techniques are considered. The genetic algorithms approach most effectively minimized traffic network disruption, because it directly minimizes changes in traffic performance. Techniques that rely on the implementation of a neural network are computationally expensive given the costs of properly calibrating the surrogate model. Therefore, among the three strategies, Corridors-optimization is the one that uses the least computational resources. Regarding interpretability of the results of the optimization, Corridors-supported optimization proved to be inspired by practical application, compared to the second explanation of the other two techniques. Hence, Corridors-supported optimization is more interpretable than the other strategies.

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